HIGH POWER SWITCHES FOR SPACE BASED APPLICATIONS

STEPHEN LEVY
U.S. ARMY LABCOM, ELECTRONICS TECHNOLOGY & DEVICES LABORATORY
FORT MONMOUTH, NEW JERSEY

JOHN L. CARTER
JOHN E. CREEDON

ABSTRACT

Today the solid-state transistor or thyristor switch satisfies the majority of terrestrial power conditioning requirements replacing the vacuum or gaseous switches of yesterday. The need for power conditioning on extra-terrestrial platforms adds another dimension to switch selection. The switch must be able to operate in the near-vaccuum of space, under high but variable radiation levels and be compatible with the thermal management system of the space vehicle. The choice of the type of switch is no longer obvious and it may be desirable to go back and consider other types of switches.

INTRODUCTION

All of the switch requirements for space-based power conditioning cannot be completely satisfied by any one of the existing switch technologies. This makes it necessary to go back and examine all of the basic generic switch technologies, and make an assessment as to the more promising research and development approaches. Approaches that have been considered in the past for more conventional power conditioning applications must be reconsidered with respect to these new requirements.

SWITCH REQUIREMENTS

The prime power systems being considered for space applications are listed in Table 1 below:

POWER CONVERTER	VOLTAGE volts	FREQUENCY hz
CHEMICAL DYNAMIC ALTERNATOR	10-100,000	200-1000
NUCLEAR DYNAMIC ALTERNATOR	10-100,000	200-100
NUCLEAR STATIC TI[1]	10-50	DC
NUCLEAR "STATIC" MHD[2]	1-50,000	DC
FUEL CELLS	100-500	DC
BATTERIES	100-1,000	DC
CHEMICAL DYNAMIC HPG[3]	50-500	DC
NUCLEAR DYNAMIC HPG[3]	50-500	DC

TABLE 1: SPACE BASED PRIME POWER CONVERTERS

NOTES:
1. TI - THERMIONIC/THERMOELECTRIC CONVERTER
2. MHD - MAGNETO-HYDRODYNAMIC
3. HPG - HOMOPOLAR GENERATOR

The prime power converters are divided according to their voltage requirements. The low voltage converters (up to a few hundred volts) being considered for multi-megawatt generation include thermionic or thermoelectric, fuel cells, homopolar generators and batteries. The high voltage converters (in excess of a few hundred volts) are the chemical turbines driven alternators and MHD. The voltage level dividing the two groups is somewhat arbitrary, but is realistic as far as solid-state switch technology is concerned.

The prime power converters are further divided according to whether the power source is nuclear or chemical. The nuclear sources can be used to power the thermionic or thermoelectric, the alternator or homopolar converters. Certainly the thermionic and thermoelectric would be nuclear powered.

SWITCHES FOR LOW VOLTAGE OPERATION

Environmental Constraints

The most severe switch requirements are those associated with a nuclear source mated with a low voltage converter. There is a radiation hardness requirement associated with the extra-terrestrial environment which can affect the choice of switches, however, the switches closest to the nuclear source will be subject to a high radiation environment for many years of continuous exposure and must be able to function during its life without degrading past established limits. The very high currents expected for multi-megawatt operation at low voltages demands that the inverter switch(s) must be located as close as possible to the generating converter to keep efficiency as high as possible. The nuclear source must be placed some distance from the load to avoid radiation damage to the load electronics, dictating relatively long power transmission distances. This requires that the front end of an ac - dc or dc - dc inverter be positioned in the reactor source area to step up the chopped converter voltage to higher voltages and reduced currents to save on conductor size and weight. This results in the need of a switch type that can operate in a high nuclear radiation environment, or by protecting the switch with shielding, stay within its radiation tolerance. This same switch type must be able to operate at high temperatures otherwise extensive thermal radiators would be required as well as the radiation shielding. The switch type that was radiation and temperature limited would demand the combination of radiation shielding and thermal radiators imposing a severe penality for the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1987**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **High Power Switches For Space Based Applications**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. ARMY Labcom, Electronics Technology & Devices Iaboratory**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT
Today the solid-state transistor or thyristor switch satisfies the majority of terrestrial power conditioning requirements replacing the vacuum or gaseous switches of yesterday. The need for power conditioning on extra-terrestrial platforms adds another dimension to switch selection. The switch must be able to operate in the near-vaccuum of space, under high but variable radiation levels and be compatible with the thermal management system of the space vehicle. The choice of the type of switch is no longer obvious and it may be desirable to go back and consider other types of switches.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**6**	

weight and size of the space platform.

The combined space and nuclear environmental switch requirements are still being developed in the SDIO Space Power Architecture studies. The worst case requirements for the inverter switch close to a nuclear source could be as high as 10^{13} N/cm^3 and 10^9 Rads with a switch ambient temperature as high as 700^{o}C.

The payoff in the size and weight of the thermal management system with increasing temperature is high enough to justify a major effort to increase the ambient operating temperature of the switch to high as possible. These radiation environmental requirements can be relaxed if the inverter does not have to operate near the nuclear reactor, or if size and weight restriction permits significant shielding, or finally, if the power source is non-nuclear.

Constraints Imposed by Low Voltage Operation

In addition to the requirements for radiation hardness and high ambient operating temperatures imposed by a nuclear power source, the switches for space-based inverters operating from low voltage prime power converters, must possess the following additional features:

- o low forward (voltage) drop,
- o fast forward and reverse recoveries,
- o high gain,
- o inherently low inductance,
- o geometry suitable for high heat transfer,
- o controllable high current density, and
- o long term stability, reliability.

The most critical switch characteristics is low voltage drop at high multi-megawatt operation. Forward voltage drop in a low voltage inverter has a critical impact on the efficiency of the inverter, for example, a 1 volt drop for a 30 volt switch is 3.3% change in efficiency, but only a 0.2% change for a 500 volt switch. Operating efficiency is a key issue because of the difficulty of disposing of waste heat. The difference between a 94% and 96% efficiency is small when considering the percentage of power delivered to the load, but large when considering that the radiator size must be increased by 33%. The goal for switch efficiency is >95% for converter outputs below 100 volts and >99% above 100 volts.

In the selection of switches for low voltage space inverter applications, a trade-off between other characteristics such as ambient operating temperature or radiation resistance must be considered. As an example, a switch with reduced radiation resistance but higher temperature operation may result in an optimum power conditioning system. The reduced size and weight of the thermal radiator may be greater than the increased shielding weight.

Fast recovery improves switching efficiency permitting higher switching frequency operation. In general this results in a reduction in the size and weight of magnetic and capacitive components up to a certain switching frequency limit. This limit is established by the balance of the size and weight of magnetic and capacitive components with the increased losses with frequency of the transformer core and output rectifiers.

SWITCHES FOR HIGH VOLTAGE OPERATION

Constraints Imposed by High Voltage Operation

The high voltage switch requirements excluding radiation and ambient operating temperature, differ from the low voltage switch constraints in the following ways:

- o low reverse leakage,
- o high noise immunity to false triggering,
- o high voltage insulation with good thermal properties,
- o immune to dV/dt and dI/dt failures,
- o high degree of isolation between switch and driver, and
- o minimal variations of electrical properties between switches.

The requirement for low reverse leakage is imposed by the dissipation that would develop under high voltage operation which would reduce the converter efficiency and reduce switch reliability. The high noise immunity to false triggering is important to inverters as the load or source induced high frequency voltage variations could capacitively couple to the gate of solid-state devices, causing unwanted operation. With high voltage operation comes the additional need for high voltage insulation between device and the rest of the circuit. Most insulators are poor thermal conductors limiting the choice of semi-conductor insulators to diamond, beryllia or to selected anisotropic materials. The problems of lattice matching, or bonding the semi-conductor to the substrate creates additional constraints. The other characteristics can at least be approached with silicon power semiconductor available at the present time.

The characteristics of silicon based power semiconductors now available, are listed below.

THYRISTORS	>500 VOLTS WITH CURRENT >3000 A	SWITCHING ENERGY TEMPERATURE RADIATION EFFECTS SPEED
POWER TRANSISTORS	<500 VOLTS, MEDIUM POWER	GATE DRIVE TEMPERATURE RADIATION EFFECTS
POWER FETS	LOW VOLTAGE <500 V HIGH FREQUENCY MEDIUM CURRENT <300 A	LOW TEMPERATURE RADIATION EFFECTS
GTOs, SITs	HIGH VOLTAGE >500 V HIGH CURRENT >1000 A	HIGH SWITCHING ENERGY LOW SWITCHING FREQUENCY, TEMPERATURE RADIATION EFFECTS
MCTs	HIGH VOLTAGE >500 V MEDIUM CURRENT 150 A - 1500 A	MEDIUM TEMPERATURE <300^o C RADIATION EFFECTS

TABLE 2: EXISTING CLASSES OF POWER SOLID-STATE SWITCHES THEIR APPLICATIONS AND LIMITATIONS

None of the silicon semiconductor devices listed completely satisfy the space-based inverter requirements. The power FET's show promise for low voltage switching applications. A typical device has a breakdown voltage of 100 volts and an on resistance of 40 milliohms. The switching time is less than 50 nanoseconds. The devices can be paralleled because of their positive temperature coefficient, which encourages inherent equalized current sharing. Therefore, it is possible to achieve very low switching loss by putting a large number of devices in parallel. A second characteristic of the power FETs is their very high speed switching at frequencies up to 1000 Hz and higher. Very rapid transition time minimizes the power loss between the off-state and the conducting-state. With this rapid switching frequency, magnetic components can be made smaller and more efficient.

The MCT (MOS Controlled Thyristor) shows promise for high voltage (>500 V) space-based inverter applications. The major advantage of the MCT is its low switching energy, combined with low forward voltage drop.

A device not mentioned in the table because of its early phase of development is the Deep Impurity, Double Injection switch. The Deep Impurity, Double Injection $(DI)^2$ devices have potential to satisfy both low voltage and high voltage space inverter power supply applications.**(2)** This family of semiconductor devices is based on bulk effects of deep energy level impurities, such as, gold and electron irradiation in silicon, and chromium and oxygen in gallium arsenide. The deep energy level impurities enhance, active-charge dynamic interactions, in the mid-range of the semiconductor bandgap, aside from simple bimolecular recombination. The initiation and control of these bandgap interactions, expand the range of device applications as compared with ordinary P-N junction devices.

These new semiconductors have the potential to raise the switching voltage by a factor of ten, operating temperatures to 300° C and radiation levels to gigarads (Si) gamma. The $(DI)^2$ device development has not progressed to the point where typical electrical performance characteristics can be predicted. Diodes have been constructed and irradiated to the gigarad level. The diodes demonstrated stable switching parameters both before and after irradiation.

Other Materials Suitable for High Voltage Inverter Switches

Gallium Arsenide semiconductor power devices are also an alternative to silicon based power semiconductor devices for space-based applications.**(1)** Gallium Arsenide devices have the potential of operating at temperatures of (300°-400° C) a substantial improvement over silicon (<200° C). The material also has significantly higher radiation resistance than silicon. In addition, to the above advantages GaAs devices will be several times smaller than silicon devices with the same performance with significantly faster switching times. Experimental results on very small thyristor devices with an area of approximately 1 mm^2 have been reported. Current densities in excess of 1,000 $amps/cm^2$ were obtained. At 1,000 A/cm^2, the on-state voltage drop was between 1.6 and 2.2 volts.[18] GaAs FETs have at least 10 times lower on-resistance per unit areas than silicon, while having the added benefit of faster switching speeds. The possibilities of GaAs based power semiconductors have up to now remained largely unrealized. The reason for this has been the substantial non-uniformity of the available material. The development of GaAs power high voltage switches will require highly advanced technology, such as very high purity n-type epitaxial layers with doping levels below $10^{16}/cm^3$ and good mobilities; the fabrication of high voltage p-n junctions; and the ability to invert the surface of p-type GaAs to obtain n-channel MOSFETs. In order to realize the potential of GaAs power devices techniques for fabricating large area, uniform GaAs material must be developed[19]. There is renewed interest in SiC and Diamond as semiconductor materials. These materials are expected to impact the long term needs of power semiconductor physics and will not be discussed in this paper.

ALTERNATIVES TO POWER SEMICONDUCTOR DEVICES

Because of the present temperature limitations of available semiconductors and the need for high ambient temperature operation and high nuclear radiation resistance, it is desirable to consider other alternative switches. These alternative switch technologies include the following:

- o vacuum devices,
- o plasma switches such as the Crossatron, the Tacitron, and
- o self switching thermionic converters.

Vacuum Arc Switch

The most promising vacuum device is the vacuum arc switch, developed by Gilmour, and his associates, at the University of Buffalo.**(3)** This device has potential application for use with a high voltage, prime power converter. The radiation resistance, and high temperature operation can be extrapolated from tests made on similar generic devices. The major disadvantage of the vacuum arc switch is the high switching energy required. The performance characteristics of a typical vacuum arc switch are listed in Table 3.

Voltage Hold Off	-15 kV symmetrical
Forward voltage drop	-20 volts
Switching Time	-100 usec.
Switching Energy	-High (magnetic)
Maximum Operating Temp.	-700°C
Radiation Resistance	-Good
Plasma Source	-Cold Cathode

TABLE 3: THE VACUUM ARC SWITCH

Crossatron Switch

A number of plasma devices deserve consideration for space-based applications. There is a large amount of experimental data that demonstrates that gaseous plasma devices can meet the radiation, and temperature requirements. One device that shows promise is the Crossatron.**(4)** This device was developed at Hughes Aircraft, by Harvey and Schumacher. The performance characteristics of this device are listed in Table 4.

Hold off Voltage	-33 kV
Peak Interrupt Current	-1500 A
Forward Voltage Drop	-200 V
Closing Time	-1 usec.
Opening Time	-2 usec.
dV/dT	-10 kA/us
Switching Energy	-8 J
Plasma Source	-Cold Cathode
Operating Temperature	-700°C

TABLE 4: CROSSATRON PERFORMANCE CHARACTERISTICS

The major advantage of the crossatron is that it is a cold cathode plasma device that requires no heater power and high switching rates (>100 kHz). A plasma switch that requires heater power suffers from the fact that the amount of heater power often exceeds the switch commutation loss. The crossatron has potential high voltage inverter applications. Its limitations are its high voltage drop (>200 V), high switching energy, low repetitive controllable current density (10 A/cm^2) and complex gate drive circuitry.

Tacitron Switch

The tacitron is a second gaseous plasma device that should be considered for space-based inverter applications. The tacitron was conceived in this country in the early 1950's.**(5)** The tacitron is a modified thyratron that has the capability of rapidly switching current on and off without removing the anode voltage. The early models contained noble gases, such as xenon, which is not suitable for low voltage operation. Major advances in this area have been made by the Soviets. Tubes containing both barium and cesium vapor have been extensively investigated in USSR. The barium lowers the emitter work function, and the cesium, with its low ionization potential, provides the necessary ions. The estimated achievable performance characteristics for the cesium vapor tacitron is presented in Table 5.

PEAK ANODE VOLTAGE	....	250 VOLTS
INTERRUPT CURRENT	....	100 AMPS
FORWARD VOLTAGE DROP	....	0.5-1.0 VOLTS
SWITCHING FREQUENCY	....	20 KHZ
OPERATING TEMPERATURE	....	>1000°C
TURN ON TIME	....	1-2 US
RECOVERY TIME	....	4-5 US
SWITCHING ENERGY	....	LOW

TABLE 5: PERFORMANCE CHARACTERISTICS OF CESIUM VAPOR TACITRON

The switching energy required for the cesium vapor tacitron is uncertain at the present time, though it is expected to be low because of the low ionization potential of cesium. However, the tacitron construction is similar to a thyratron with a modified grid structure and require a complex switching circuit. This will present a problem for an inverter placed close to a nuclear source. The ambient operating temperature of the device is very high between 1000 and 1800°K. These devices require a high temperature emitter with a low work function. The energy cost of heating this emitter with electric power would be prohibitive. The tacitron switch can only be used for inverter applications where significant waste heat is available, such as, thermolelectric and thermonic systems and can be integrated into the heat pipe design if required. The cesium vapor tacitron is not an attractive switch for use with other low voltage, prime power converters, such as batteries, and solar systems.

Self-Switching Thermionic Converter

The self-switching thermonic converters have the advantage of eliminating all of the auxiliary components listed above, except the transformer. The proposed device is based on the high frequency oscillations observed in thermonic power converters. The same type of oscillations have also been observed in cesium vapor tacitrons. In the thermonic converter natural oscillations occur at some combination of emitter and reservoir conditions. In 1963, Oppen proposed a simple scheme whereby the natural two mode (ignited/unignited) operation of a thermionic diode could be used to raise the nominal output voltage from 0.3 to typically 28 V.**(6)** The concept was to switch the diode between these modes to deliver a pulsing dc current to a load, via a transformer. Losses in the primary circuit were minimized by connecting the thermonic converter directly to the transformer without intermediate switches. The idea made use of the dual-mode, current-voltage, "hysteresis" behavior in pulsed diode operation. The power required for pulsing was low and could be supplied as part of that thermonically generated. Unfortunately, experimental results established that the speed of the diode turn-off was governed by the time to extinguish the arc. This time was a minimum of 1 millisecond, much to long for high repetition rate operation. Spontaneous coherent oscillations have been observed in thermonic diodes by several investigators. The oscillations are usually non-sinisodial and consist of modulation of the diode current as a result of space charge fluctuation in the interelectrode space. Houston has reported on the characteristics of these oscillations. Typical data is presented in Figure 1.**(7)**

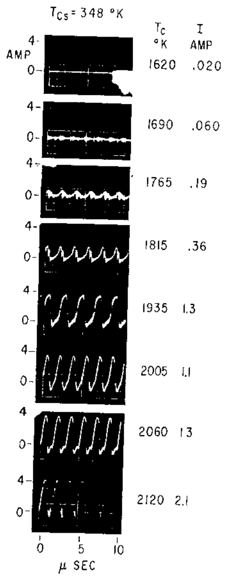

Fig. 3 Oscillation waveform across an 0.05 ohm load (a precision shunt) connected between cathode and anode. The pyrometrically-determined cathode temperature and the direct current are shown beside each photograph.

The data indicates that the oscillations can be controlled by a combination of load impedance and diode temperature. This concept has the potential of achieving an AC thermonics converter that would have a number of advantages:

- o No Inverter Switch Required,
- o Frequency can be Chosen and Maintained,
- o Complete In-Pile Operation,
- o No Control Circuitry Required,
- o Radiation Hard and High Temperature Operation, and
- o Integrated Design (Source-Converter-Switch) Provides an Extra Degree of Reliability.

The major disadvantage is that this is a new approach and requires extensive research and development. Extensive information exists on thermonic diode technology, however, the proposed approach may require a trade-off between optimum power generation and optimum inverter characteristics. It also may be necessary to develop special transformer technology to step-up the voltage and control to load impedance presented to the thermonic converter.

The development of an inverter power supply for a high radiation and temperature environment requires the consideration of other components besides the switch. The control circuits, energy storage capacitors and inductive components, must also be able to operate in the high temperature and radiation environment. These components are not available and must be developed.

CONCLUSIONS:

The selection of a switch for space-based inverter applications requires a trade-off between package size, weight requirements and reliability. The reliability is highly dependent on the power conditioning system environment. The two key environmental parameters are nuclear radiation hardness and temperature. The trade-off analysis must include all components of the power package. The major components of the power package are; prime power, power conditioning and power transmission to the load. The power conditioning system must include all the auxiliary components including; thermal management systems, driver circuits, fault protection and energy storage.

The switch choices for the near term (<2010) will differ from those made for the far term (>2010). Devices that hold promise for the near term are the MCT, FETs, Crossatron, and possibly the first GaAs power semiconductors. All the near term switches considered will require a size and weight penalty to overcome performance and environmental deficiencies. Far term switches at this time include; deep impurity silicon, more advanced gallium arsenide, silicon carbide, and diamond power devices. The self-switching thermonics converter is a plasma device that is worth consdering for long term space-based power conditioning applications.

REFERENCES

1. S. N. Vainshtein, I. I. Diakonu, Yu. V. Zhilyaev, M. E. Levinshtein, "Fundamental Switching Parameters of Gallium Arsenide Thyristors," Sov. Phys. Tech. Phys. 28(3), March 1983.

2. G. R. Sundberg, "A New Very High Voltage Semiconductor Switch", 1985 Power Electronics Specialists Conference (PESC), June 24-28, 1985.

3. A. S. Gilmour, Jr., R. F. Hope III, R. N. Miller, "10 KHZ Vacuum Arc Switch Ignition", Proceedings of the 14th Modulator Symposium, June 1980, pp 80-84.

4. R. W. Schumacher, and R. J. Harvey, "Crossatron Modulator Switch", Proceedings of the 16th Modulator Symposium, June 1984, pp 139-51.

5. V. B. Kaplan, A. M Martsinovskii, A. S. Mustafaev, V. I. Serbin, V. I. Sitnov, A. Ya. Ender, and V. G. Yur'ev, "Pulsed Control with a high-Current Low-Voltage Cesium-Barnum Discharge", Soviet Physics Technical Physics, Vol. 22, No. 10, Oct., 1977, pp. 1201-7.

6. W. R. Oppen, Thermionic Conversion Specialist Conference, Gatlinburg, Tenn., October 1963, p. 372.

7. J. M. Houston, "Oscillations in Cesium Themionic Converters", 22 nd Annual Conference Physical Electronics, March 2-3, 1962 MIT.

8. T.R. Burkes, "An Assessment of Switching Technology in the USSR, Supplement III - Solid State Switches", Contract DAAK 21-82-C-0111, US

Army Fireign Science Adn TEchnology Center, Charlottesville, VA, 18 May 1986, page 7.

9. W.M. Portnoy and M. Kristiansen, "Workshop on Solid State Switches for Pulsed Power", Contract DAAG29-81-D-0100 under Delivery Order 0424, Final Report dated May 31, 1983, US Army Research Office, pages 89-96.